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Reliability analysis of the internet of things using Space Fault Network

Shasha Li [a], **Tiejun Cui** [b,c,*], **Muhammad Alam** [d,e]

[a] *School of Business Administration, Liaoning Technical University, Huludao, Liaoning 125000, China*
[b] *College of Safety Science and Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China*
[c] *Tunnel & Underground Structure Engineering Center of Liaoning, Dalian Jiaotong University, Dalian, Liaoning 116028 China*
[d] *School of Engineering, London South Bank University, London, UK*
[e] *Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

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Abstract The Internet of Things (IoT) is a network topology structure based on the interconnection of many nodes. It realizes the basic functions of IoT through the transmission of information, data, and energy between the nodes. To study the reliability of Internet of Things Network Topology (IoTNT) structure, we must abstract IoT as network topology and study the reliability of the network itself from the topology structure. This paper attempts to apply the Space Fault Network (SFN) to the study the reliability of IoTNT. To achieve this goal, the nodes and edges of IoTNT are equivalent to events and connections of SFN respectively. A structure analysis method based on SFN is proposed and used to study the reliability of IoTNT. At the same time, the influence of possible logical relationship between nodes on the reliability of IoTNT is studied. According to the SFN structure representation methods (SFNSRMs), considering different network structures and induced modes, the analysis methods and calculation methods of the evolution process of target event are given. An example is given to illustrate the analysis and calculation process. The research provides the new methods for the reliability study of IoT and the development of SFN.

1. Introduction

Internet of Things (IoT) is the next generation of internet innovation. The innovation is the core of IoT development. The essence of IoT is in three aspects. First, the characteristics of the internet, that is, the network structure of interconnection and interoperability for the things that need to be networked. Second, the characteristics of identification and communication, that is, IoT objects must have the function of automatic

* Corresponding author at: College of Safety Science and Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China.
E-mail addresses: cuitiejun@lntu.edu.cn (T. Cui), alamm52@lsbu.ac.uk (M. Alam).

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identification and communication. Third, the network system should have the ability of automation, feedback and control.

The essence of IoT is based on the interconnection of networks, which link discrete events, exchanges information, data, energy and material, and forms a system to accomplish many functions. So the establishment of any IoT has a certain purpose, and IoT is relatively stable in a certain period of time and under certain conditions, so the requirement is the reliability of IoT.

At the system level, IoT is an abstract topology. All actions in IoT to achieve goals are called events, and the consequences of these events are transmitted according to Internet of Things Network Topology (IoTNT). Then according to IoTNT, different events have different processes to achieve the target events (TE). Conversely, if you follow IoTNT, completing the TE requires the cooperation of many previous events. If these events fault, the reliability of the event will change, this will affect the reliability of the TE to be achieved.

There are insufficient studies on the reliability and safety of IoT and its structure. Recent research includes the net-centric control automation of technological processes within industrial IoT systems [1]; reliable and scalable architecture for smart home environments [2]; multi-parametric analysis of reliability in IoT [3]; efficient relayed broadcasting based on the duplication estimation model for IoT [4]; dynamic power management and adaptive packet size selection for IoT [5]; Improving network lifetime and reliability for machine type communications [6]; Localized and distributed link scheduling algorithms in IoT [7]; reliability and cost of service composition in the IoT [8]; Enabling reliable and secure IoT-based smart city applications [9]; IOT performance and reliability study [10]; autonomic agent trust model for IoT systems [11]; design framework for rellability-durability risk assessment [12]; Measure Reliability for IoT Oriented Pollution Detection Software Perspectives [13]; reliability and mitigation of zero-day attacks in IoT [14]; criteria certification of smart TV for home IoT security and reliability [15]. However, these studies are still lack of methodological support at the system level and lack of generality and scalability.

For this problem, the author combines the Space Fault Network (SFN) theory to study the reliability of IoTNT. It is considered that the reliability change of IoTNT is caused by the fault of the events and connections in the network. Since each node in IoTNT exists to accomplish a certain event and the fault or reliability change of the event is caused by the fault or reliability change of the event in the earlier stage, the process is the transmission process of fault or reliability change between events. This process conforms to the characteristics of system fault evolution process (SFEP) [16], and SFN is a theory established for the study of SFEP.

SFEP [16] exists widely in various fields, affecting production safety. The system fault does not occur instantaneously, but an evolution process. This process has experienced many events and is influenced by many factors, which make SFEP diverse. These diversities are all patterns of system fault, and each pattern is a possibility, but the possibilities are different. The actual SFEP is only one of them. Therefore, how to analyze all the possibilities of SFEP and determine which evolution process is more likely to occur is of great significance for ensuring the safe operation of the system and maintaining its reliability.

In SFEP, system refers to the natural system and the artificial system. Natural system disaster evolution is a process in which natural disasters occur and develop according to natural laws, and it has nothing to do with human participation. The artificial system fault evolution is the process that system occurs a failure, which established by people according to the natural characteristics of things for a given purpose. They are all SFEP. Research on SFEP is still in a preliminary stage. SFEP has its own characteristics. (1) There are many reasons for SFEP, and it is difficult to determine the relationships between the reasons. (2) In SFEP, the evolution from edge event (EE) to TE is a complex network structure. (3) The network structure cannot use simplification method to delete events and their relationships. (4) Cause event (CE) has multiple logical relationships leading to result event (RE); (5) there are many factors influencing the evolution process. (6) Whether various factors and reasons are independent or interrelated. These problems are difficult to describe using the current system structure analysis methods. They bring difficulties to the further study of SFEP, and the reliability of IoTNT is just a case in the specific field of SFEP.

However, the research on SFEP has been increasing in recent years. The research contents include mechanical system fault evolution [17], grid cascade fault evolution [18], multi-focus strategy optimization model [19], competitive fault model [20], hybrid fault model [21], multi-strategy evolution dynamics [22], online knowledge system evolution [23], innovation ecosystem performance [24], urban transportation system evolution [25], enterprise system evolution [26], software spatial structure evolution [27], Enterprise system evolution [28] and behavior process evolution [29], etc. The structure representation and analysis methods of the system are relatively few. They have been studied and applied in medical field [30], project management [31], software evaluation [32], health analysis [33], monitoring video analysis [34], parallel structural analysis [35], teaching activity analysis [36], etc. These studies are generally aimed at specific industries, based on the basic characteristics of industries and disciplines. Therefore, their abstraction is not enough to form a general SFEP description and analysis method. Moreover, the study of IoTNT from the SFEP has not yet appeared.

In 2012, the Pro. CUI proposed the SFT to analyze the relationships between influencing factors and reliability. It includes the SFT theoretical basis [37], intelligent SFT [38,39], SFN [40,41], system movement space and system mapping theory. At present, SFN methods are based on SFT, so SFN must be converted into SFT, and then analysis. But this method is not for the network structure of SFN. To study an independent SFN analysis method, the SFN structure representation method (SFNSRM) using the matrix of cause event and result event (CERE) to describe SFN is proposed. Qualitative and quantitative analysis of SFEP using matrix and related operations is beneficial to the intelligent processing of computer. However, SFNSRM(I) cannot represent the case where multiple CEs cause RE through different logical relationships. Based on SFNSRM (I), SFNSRM (II) is proposed to solve this problem. It lays a foundation for SFNSRM and computer intelligent processing.

In summary, the main purpose of this paper is to study SFEP at the system level, propose a structure representation method of SFN, and study the logical relationships between events. Furthermore, the reliability of IoT is described with SFEP. Event fault and reliability change in IoTNT are represented and studied by SFN, which provides a basic theoretical method for discussing the reliability of IoTNT from the structure. It is also the first time that SFNSRM has been demonstrated internationally and applied to IoT reliability analysis.

The paper consists of seven sections. Section 1 introduces background; Section 2 gives an overview of SFEP; Section 3 gives an overview of SFT; Section 4 explains the equivalence of IoT and SFN; Section 5 studies SFNSRM(I); Section 6 studies SFNSRM(II); and Section 7 gives some conclusions.

The relevant definitions are given as followed. The following definitions are given in the author's literature.

SFN: A network structure consisting of system fault events and their logical relationships, denoted by $W = (V,L,R,H,\text{B})$, where: V is the set of nodes (events); L is the set of connections in the network; R is the set of network spans; H is the set of network widths; B is a Boolean algebraic system.

Probability of Event Occurrence (PEO): PEO has the same definition as SFT [37].
Edge Event(EE): The most basic event that causes the target event.
Process Event(PE): Events between edge events and target event.
Target Event(TE): Events that need to be studied and concerned in SFEP.
Causal Event(CE): Events that lead to other events.
Result Event(RE): Events caused by other events.
Connection: Transfer of impacts between events during SFEP.
Transfer Probability (TP): The probability that CE can cause RE.
General Space Fault Network(GSFN): A network without ring structure.
Multidirectional Ring Space Fault Network(MRSFN): There are two evolution paths in the network, which start at the same event and end at the same event.
Unidirectional Ring Space Fault Network(URSFN): There is an evolution path in the network, which connects the end to the end, and any event can be used as a EE or TE.
Edge Event Induction Fault Evolution Process(AEIFEP): EEs and PEs both occur and lead to TE, and the occurrence of TE is parallel to all participating event.
All Event Induction Fault Evolution Process(EEIFEP): EEs lead to subsequent PEs and eventually TE, which is a progressive relationship.

2. System fault evolution process (SFEP)

SFEP is a phenomenon that exists widely in production and life, and it involves a wide range of contents. Generally, it can be divided into natural system disaster evolution and artificial system fault evolution. Natural system refers to the non-man-made system in the natural environment. It evolves according to natural laws, such as earthquakes, landslides, haze and storms. Artificial system refers to a system which is manufactured according to natural attributes and laws and can be controlled under certain conditions in order to achieve the predetermined goal, such as machine, aircraft. Of course, it can also include non-material systems such as social systems.

The structure of SFEP is complex. Macroscopically, the evolution process is formed by the development of many events in a certain logical and order. Microscopically, it is the interaction and causality between events. So there are still some difficulties in describing SFEP. For example, the definition of evolution system, different boundary conditions can produce different EEs and TEs, and even affect the evolution process. For another example, the division and determination of each event, the scale of division is different, and the event and evolution process will also change. The causal relationships among events are difficult to obtain directly for some process events (PEs). In the process, various factors have different effects on events, logical relationships between events and evolution order, and the correlation of factors is difficult to determine.

But SFEP is a problem that must be studied. Literature [41] gives a description of the first stage fault process of three-stage reciprocating compressor. By summarizing and describing the process, it can be seen that the first stage SFEP of compressor is related to many components and their occurrence events. The faults of these components are at least affected by temperature and pressure factors. At the same time, fault characteristics are contained in real-time monitoring data. Therefore, it is necessary to analyze component fault, accident interaction, fault causality and fault transmission of components through fault data and influencing factors.

The Pro. CUI considers that the process of rock burst is a complex dynamic system evolution process [42]. There are many influencing factors. It is difficult to effectively explain the complex disaster evolution process of coal (rock) deformation, crack development, flying rock projection and collapse through mechanical experiments and field data without systematic study. It is difficult to study the evolution process of rock burst without knowing the logical relationship of each event and the role of each factor in the process.

Similarly, there are many disaster factors and monitoring data involved in the study of open-pit mine disaster evolution [43], and the major disasters such as surface deformation, water pollution and atmospheric pollution are analyzed. They are interacting with dozens of factors, such as mining activities, water, fire, vibration, etc.. However, the existing methods are difficult to describe the evolution process of these disasters, determine the influencing factors, analyze the disaster data, divide the stages and abstract characteristics, which make the next step of research and prevention facing great difficulties. These difficulties and problems put forward an urgent need for SFEP research.

3. Space fault tree (SFT)

The author has studied the basic theory of safety science for a long time, focusing on the relationships between system reliability and factors. SFT includes four stages. The theoretical basis of SFT is proposed to study the relationships between factors and system reliability. Intelligent SFT uses intelligent science and big data technology to transform SFT, makes it have the ability of fault big data processing and logical reasoning. SFN is used to describe the SFEP. System movement space and system mapping theory measure system movement and the relationships between factors and data. SFN is the third stage of SFT. Because the SFT can only be used to describe simple SFEP with tree structure, it is difficult to generalize. SFN is proposed on the basis of SFT, and the complex SFEP is described by using network topology. It is more suitable for general complex evolution process.

SFN formed by SFEP is different from general network because of the particularity of fault causality. For example, digraph matrix can be transformed into Hasse matrix by Hasse transformation. This is achieved by retaining the maximum path between two points and deleting the non-maximum path. Each node can be connected by the simplest path, which is convenient for computer processing and reduces the network complexity. But this method can not be realized in SFN logically. Because each event in SFEP can lead to the same result in different evolution paths. Or two events can be connected through multiple evolution paths. Therefore, these evolution paths cannot be simplified, because these paths are both a fault mode and a possibility.

Previous studies on SFN have been carried out by converting SFN into SFT. Because SFT has achieved fruitful results, it can deal with fault big data analysis, causal logic reasoning, and system reliability structure analysis and so on. However, it is based on the tree structure and function relationship, which is not suitable for computer intelligent qualitative and quantitative analysis. Therefore, in order to adapt to computer intelligent processing, it is necessary to design a computer-oriented structure analysis method for SFN. SFN is stored in matrix form, and SFNSRM is used to analyze SFEP qualitatively and quantitatively through matrix and database operation.

4. Equivalence of IoT and SFN

Before proceeding to the next step, two questions have to be clarified. One is whether the reliability change process of IoT can be described by SFEP; the other is whether there is equivalence between IoTNT and SFN.

IoT is changing rapidly in different industries and fields. It must be abstracted to the system level, not the professional field, before research. Before abstraction, IoT could be regarded as the interconnection of many events, exchange of information, data, energy and matter, and finally completing the TEs needed to be completed in IoT. From the network structure, IoT can be regarded as the IoTNT established according to the network structure, which is composed of many events and many connections. The fault of any TE in IoTNT is related to network structure, related connections and events.

Different event faults, or different connection faults, will lead to changes in the reliability of the TE. For the TE in IoT, its reliability changes are directly related to previous events. Macroscopically, many events occur in accordance with a certain logical relationship. Microscopically, it is caused by the causal relationship between two events. This is the same as the basic characteristics of SFEP, so SFEP is very suitable for describing and studying IoT reliability.

Since SFEP is suitable for describing and studying IoTNT, it is necessary to determine the equivalent relationships between the components of IoT and SFN. From the previous paper of literatures, IoT can be abstracted as IoTNT to study its reliability changes. IoT is mainly composed of a variety of behaviors (different technology domains are different) to achieve a goal, the relationships between behaviors, and the topological structure of behaviors and relationships. IoT is abstracted as IoTNT, and all kinds of behaviors are equivalent to nodes. The relationships between behaviors are equivalent to the edges between nodes. IoTNT is composed of these nodes and edges.

Furthermore, SFN describes IoTNT from SFEP, and the goal achieved by IoT can be regarded as the TE of SFN. The TE may be any behavior that IoT needs to accomplish. The related nodes correspond to the EEs, PEs and TEs of SFN. EEs refer to the edge nodes or the starting nodes of reliability analysis in IoTNT. PEs refer to nodes between EEs and TEs in IoT. The edges in IoTNT refer to the connections in SFN. The connections have directions, from CEs to REs, and imply TP.

IoT can be abstracted as IoTNT and described by SFN from SFEP. Therefore, the reliability study of IoT can be implemented by SFN at the system level. The description and research methods of SFEP will be discussed in the framework of SFN. These methods are generally applicable to SFEP analysis in various fields, and also to reliability analysis of IoTNT. At the same time, the examples listed below can also be equivalent to IoTNT examples.

5. SFN structure representation Method(I)(SFNSRM(I))

The SFEP described by SFN is analyzed qualitatively and quantitatively. SFNSRM(I) is put forward, namely CERE(I) and its related methods. SFNSRM(I) is an independent research method based on SFN network characteristics, which are different from the previous SFT methods. It is the foundation of the independent research SFN. The related definitions, steps and computation procedures are given below.

Table 1 is the CERE(I) of SFN. The table reflects the causality of events in the SFEP. ce_n is used to denote a specific CE, $n = 1,\ldots,N$; re_m to denote a specific RE, $m = 1,\ldots,M$. Use CE to denote the set of ce_n, $CE = \{ce_n | n = 1,\ldots,N\}$; RE denotes the set of re_m, $RE = \{re_m | m = 1,\ldots,M\}$. This is slightly different from the CE and RE representations in SFN, because the original definitions do not cover the CE set and the RE set. In order to expound and deduce, this paper modifies them. The CERE(I) indicates SFEP, which does not require the connections in the SFN structure, but requires TP. Therefore, in CERE(I), all the transfer relationships between ce_n and re_m are expressed by $tp_{n\to m}$, that is, the possibility of re_m caused by ce_n. In CERE(I), the set of TP is expressed as $TP = \{tp_{n\to m} | n = 1,\ldots,N; m = 1,\ldots,M\}$. Therefore, CERE(I) can be used as a table structure system, namely CERE(I) = (CE, RE, TP). It can express the relationships between all ce_n and re_m. The maximum relationship number is $N \times M$ and the minimum relationship number is N.

Definition 1. *Matrix of Causal Event and Result Event*(*I*) (*CERE* (*I*))**:** *for the structure representation of SFN, and express the causal relationships of events in SFEP, denoted by CERE* (*I*) = (*CE*, *RE*, *TP*); *the set of* $CE = \{ce_n | n = 1,\ldots,N\}$; *the set of* $RE = \{re_m | m = 1,\ldots,M\}$ *and set* $TP = \{tp_{n\to m} | n = 1,\ldots, N; m = 1,\ldots,M\}$.

Table 1 CERE(I).

	re_1	re_2	...	re_M
ce_1	0	$tp_{1\to 2}$	...	0
ce_2	0	0	...	$tp_{2\to M}$
...	...	...	...	...
ce_N	0	0	...	$tp_{N\to M}$

The number range of TP is $[N, N\times M]$. N means that each ce_n causes at least one re_m to occur, otherwise ce_n is meaningless. $N\times M$ means that all ce_n have causal relationship with all re_m. Therefore, for value of each $tp_{n\to m}$, when $ce_n\to re_m$ (CE can cause RE), $tp_{n\to m}=p_j$ (definition of TP in SFN); when $\neg(ce_n\to re_m)$ (CE does not cause RE), $tp_{n\to m}=0$. The basic structure of CERE (I) is shown in Eq. (1).

$$\begin{cases} \text{CERE}=(CE,RE,TP) \\ CE=\{ce_n|n=1,\dots,N\} \\ RE=\{re_m|m=1,\dots,M\} \\ TP=\{tp_{n\to m}|n=1,\dots,N,m=1,\dots,M\} \\ tp_{n\to m}=\begin{cases} p_j, ce_n\to re_m \\ 0,\neg(ce_n\to re_m) \end{cases} \end{cases} \tag{1}$$

We can study the macro–micro characteristics of SFEP in CERE (I), namely the causal relationships between events. In order to facilitate computer reasoning and calculation, the following structure analysis methods are given.

A. Establish CERE (I) according to the macro–micro characteristics of SFEP.

B. CE is equal to RE divided by all units in the each row of CERE(I), $CE=RE./\text{CERE}[N,1\sim M]\to ce_n=[re_{1\sim \text{M}}]./\text{CERE}[n,1\sim M]$.

C. All $ce_n\to re_m$ relationships can be expressed as $tp_{n\to m}\times ce_n=re_m$. These relationships constitute a CRS, $\Gamma=\{ce_n\to re_m|tp_{n\to m}\times ce_n=re_m\}$. The number of relationships is the same as that of $tp_{n\to m}$.

Definition 2. *Causal Relationship Set* (*CRS*): *The logical relationships of all events in CERE(I) are stored in CRS and expressed as* $\Gamma=\{ce_n\to re_m|tp_{n\to m}\times ce_n=re_m\}$. *All relationships in CRS, CE is antecedent and RE is consequent. Therefore, it is the data structure to store the causality of each event.*

D. Starting from a ce_n, according to the causality of evolution process, $re_m=tp_{n\to m}\times ce_n$ is found and re_m is used as ce_n to continue searching for its RE in Γ. Loop the process until a terminatable RE-re_m is found.

E. Terminable RE-re_m determination. According to SFEP study, the transformed SFN can be divided into three types: GSFN, MRSFN and URSFN. The terminate RE for GSFN and MRSFN can be identified in the same way, that is, the RE does not cause other CE-$ce_{n'}$ in CERE(I), then $re_m=\prod tp_{n\to m}ce_{n'},\exists(ce_n\to re_m)\in\Gamma$. URSFN is a complex structure, which represents progressive fault evolution. When a part of the evolution process has a unidirectional ring structure, let $ce_{n'}$ be the terminated RE, then $re_m=\prod tp_{n\to n'}ce_{n'}(tp_{n'\to m}ce_{n'})^k,\exists(ce_n\to re_m)\in\Gamma$, where: k denotes the number of unidirectional ring structures.

The logical relationships between EE (initial RE) and TE (terminated RE) represented by SFN are obtained for SFEP. The CERE(I) model for EE-ce_n leading to TE-re_m(This situation is called edge event induction fault evolution process, EEI-FEP) is as shown in Eq. (2).

$$\begin{cases} CE=RE./\text{CERE}[N,1\sim M]\to ce_n=[re_{1\sim M}]./\text{CERE}[n,1\sim M] \\ re_m=ce_n\times tp_{n\to m} \\ \Gamma=\{ce_n\to re_m|tp_{n\to m}\times ce_n=re_m\} \\ re_m=\prod tp_{n\to m}ce_{n'},\exists(ce\to re)\in\Gamma,\text{GSFN and RSFN} \\ re_m=\prod tp_{n\to n'}ce_{n'}(tp_{n'\to m}ce_{n'})^k,\exists(ce\to re)\in\Gamma,\text{URSFN} \end{cases} \tag{2}$$

F. According to the analysis process of TE induced by EE, the CERE(I) model of all event induction fault evolution process (AEIFEP) is given as shown in Eq. (3). The definition of AEIFEP is discussed in Section 1.

$$\begin{cases} CE=RE./\text{CERE}[N,1\sim M]\to ce_n=[re_{1\sim M}]./\text{CERE}[n,1\sim M] \\ re_m=ce_n\times tp_{n\to m} \\ \Gamma=\{ce_n\to re_m|tp_{n\to m}\times ce_n=re_m\} \\ re_m=\sum_{i=1}^{n'}(\prod tp_{i\to m}ce_i),\exists(ce\to re)\in\Gamma,\text{GSFN and RSFN} \\ re_m=\sum_{i=1}^{n'}(\prod tp_{i\to n'}(\prod tp_{n'\to m})^k ce_{n'}),\exists(ce\to re)\in\Gamma,\text{URSFN} \end{cases} \tag{3}$$

Fig. 1 shows the analysis flow of SFEP. Previous research focuses on SFN to describe SFEP, and then SFN is transformed into SFT according to transformation criteria, final SFN is studied by using existing SFT methods and results. The advantage is to make use of the existing research methods, but the disadvantage lies in the lack of analysis methods for the network structure of SFN. This paper uses CERE(I) to establish the research methods belonging to SFN.

Example 1:. *Suppose a SFEP has five events, SFEP is shown in* Fig. 2(a).

According to Fig. 2(a), $CE=\{\text{a, b, c, d, e}\}$, $RE=\{\text{a, b, c, d, e}\}$. For research, set $TP=\{0.1, 0.5, 0.3, 0.3, 0.4, 0.5, 0.3\}$. Establish CERE(I) and is shown in Table 2.

CRS is established according to Table 2, $\Gamma=\{\text{a}\to\text{b}, \text{a}\to\text{c}, \text{b}\to\text{d}, \text{b}\to\text{e}, \text{c}\to\text{e}, \text{d}\to\text{e}, \text{e}\to\text{d},\}=\{0.1\text{a}=\text{b}, 0.5\text{a}=\text{c}, 0.3\text{b}=\text{d}, 0.3\text{b}=\text{e}, 0.4\text{c}=\text{e}, 0.5\text{d}=\text{e}, 0.3\text{e}=\text{d}\}$.

Starting from event a, since $0.1\text{a}=\text{b}$ and $0.3\text{b}=\text{e}$, then $0.3(0.1\text{a}=\text{b})=\text{e}\Rightarrow 0.3\times 0.1\text{a}=\text{e}$, and $0.3\text{e}=\text{d}$, then $0.3(0.3(0.1\text{a}=\text{b})=\text{e})=\text{d}$. Further, $0.5\text{d}=\text{e}$, so $0.5(0.3(0.3\text{a}=\text{b})=\text{e})=\text{d})=\text{e}$, we can know that e and d form a in the ring structure, and the second occurrence of e is the termination event. $(0.5\times 0.3)^k\times 0.3\times 0.1\text{a}=\text{e}$, the relationship between EE-a and TE-e, namely TEPAM of e, is obtained. Similarly, the relationships between other EE and TE can also be obtained. For AEIFEP, $0.5(0.3(0.3(0.1\text{a}=\text{b})=\text{e})=\text{d})+0.3(0.3(0.1\text{a}=\text{b})=\text{e})+(0.3(0.1\text{a}=\text{b})=\text{e})+(0.1\text{a}=\text{b})=\text{e}$, then $(0.5\times 0.3)^k\times 0.3\times 0.1\text{a}+(0.5\times 0.3)^k\times 0.3\text{b}+(0.5\times 0.3)^k\times(\text{e}+\text{d})=\text{e}$, that is, TEPAM.

Combining with SFT theory, the five events mentioned above are a, b, c, d and e. In fact they are the occurrence possibilities of the event object fault or disaster. Fault occurrence probability p in SFT can be used to describe it. For an event a,

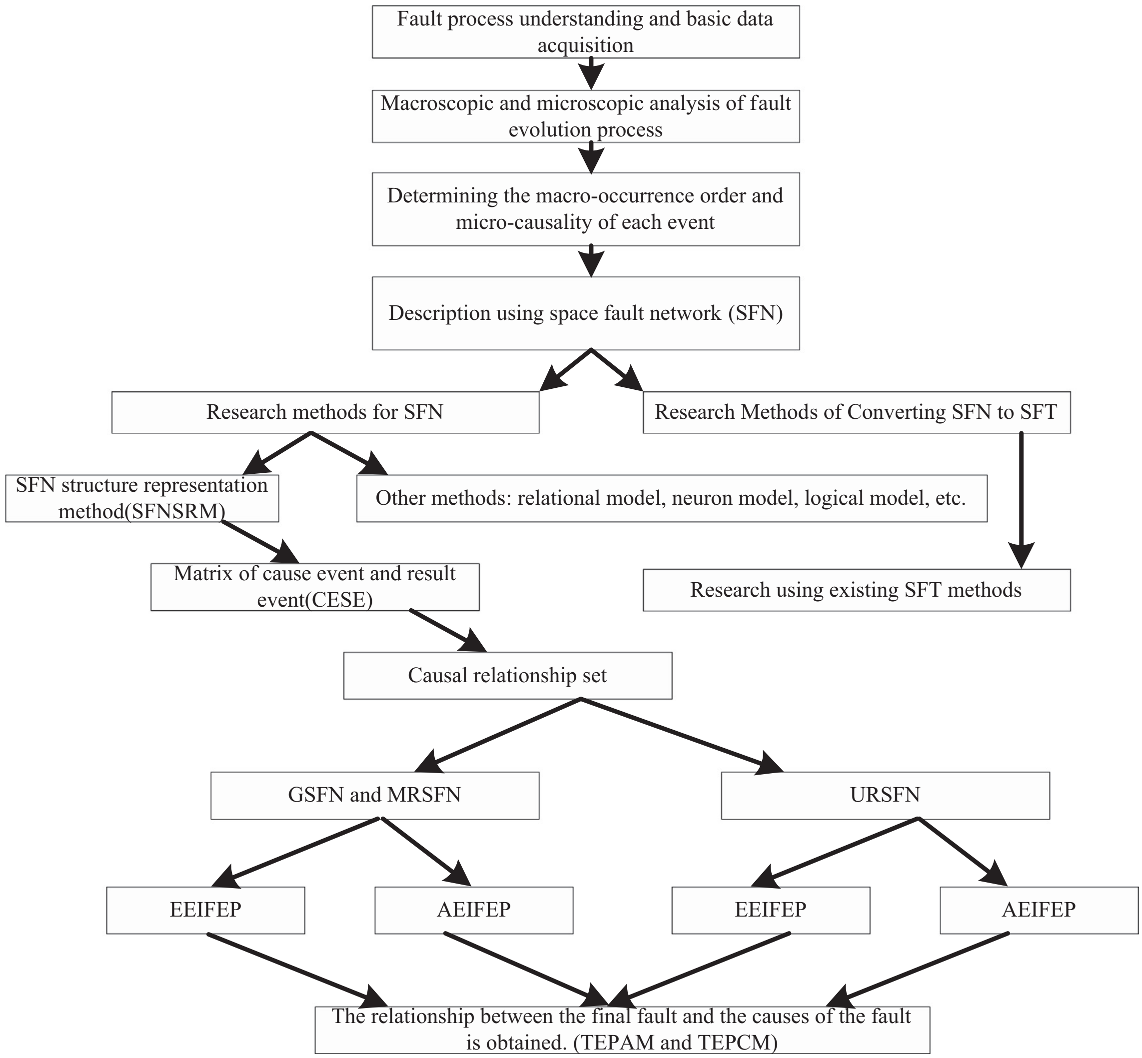

Fig. 1 Analysis flow of SFNSAM for SFEP.

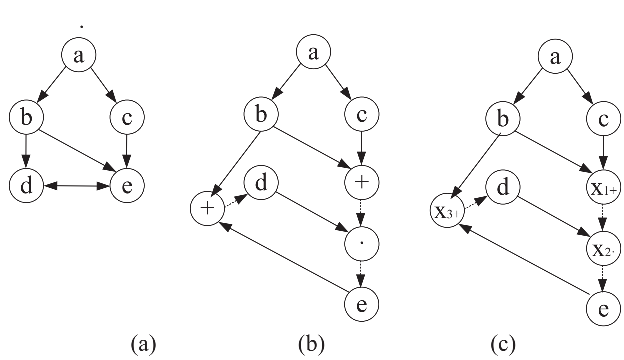

Fig. 2 Equivalent transformation of SFEP.

p_a describes the probability change under the influence of any multiple factors. It is a quantity describing the relationships between multiple factors and the occurrence of faults or disasters. p_a and Q factors together constitute $Q + 1$-dimensional space. p_a is a $Q + 1$-dimensional surface in this factor space. If the influencing factors of a, b, c, d, e are the same, then TEPCM of re_m of different CEREs can be obtained from $p_{a\sim e}$ according to network structure (GSFN, MRSFN, URSFN) and induced mode (EEIFEP, AEIFEP). The probability distribution of the TE-re_m is formed by superposition.

6. SFN structure representation Method(II)(SFNSRM(II))

Firstly, the reasons for establishing SFNSRM(II) are discussed. The structure representation of SFN mentioned in the previous section is to enable SFN to have an independent research method, rather than to be transformed into SFT for qualitative and quantitative analysis. But SFNSRM(I) has important defects.

Fig. 2(a) is a SFEP established during SFNSRM(I) research. Its characteristic is that it expresses the causal evolution relationships between events with CERE(I). However, further consideration of e as RE, its CE are b, c and d. Then, the what logical relationship combination of the b, c and d leads to the occurrence of e, which can not be expressed in Fig. 2(a) and

Table 2 CERE(I).

	a	b	c	d	e
a	0	0.1	0.5	0	0
b	0	0	0	0.3	0.3
c	0	0	0	0	0.4
d	0	0	0	0	0.5
e	0	0	0	0.3	0

CERE(I). Therefore, this shortcoming becomes the biggest problem of SFNSRM(I).

Fig. 2(b) shows a possible combination of CE-b, c and d leading to e in the original evolution process. That is to say, in the process of causing the occurrence of e, occurrence of one of the b and c can lead to the next occurrence, so b and c is "or" relationship. Event d and the results of b and c must occur simultaneously, which can lead to e. They are "and" relationships. These characteristics can not be expressed in CERE(I), so CERE (II) is constructed, and SFNSRM (II) is proposed based on them.

To satisfy the establishment of SFNSRM (II) and CERE (II), the SFEP is shown in Fig. 2(c). The logical relationships between events are marked as X_{ib}. b represents a kind of logical relationship between events, B represents the set of all logical relationships, $b \in B$. Because it mainly focuses on the research of structure representation methods, here B only includes the "and, or" relationship. In fact, it is fortunate that according to Prof. He Huacan's basic model of flexible information processing, logical relationships have been extended to 20 kinds[44,45]. These logical relationships are research in detail. The dotted arrow → in Fig. 2 **(c)** indicates equivalence connection(EC), that is, CE and RE are the same event object. But because CEs causes RE with different logical relationships, so some CEs are distinguished, the TP of EC is $tp = 1$.

Following establishes the SFNSRM (II) based on SFNSRM (I).

Table 3 is the CERE (II) of SFN. Use ce_n to denote a specific CE, $n = 1,\ldots,N$, its set $CE=\{ce_n| n = 1,\ldots,N\}$. Use re_m to denote a specific RE, $m = 1,\ldots,M$, its set $RE=\{re_m| m = 1,\ldots,M\}$. Use rs_l to represent a specific relationship event (RS), $l = 1,\ldots,L$. Use RS to denote the set of rs_l, $RS = \{rs_l| l = 1,\ldots,L\}$. CERE (II) does not require connections in SFN structures, but requires TP. In addition, RS is a logical relationship separated from an event, not an entity event, only a logical relationship among CEs that cause the RE. Therefore, it is universally stipulated that whether or not multiple CEs lead to a RE according to different logical relationships, events are separated into event entities and RSs, as shown in Fig. 2(c), event d and RS-X_3.

Compared with CERE(II) and CERE(I), the area of CERE (II) is divided into four parts, and the color background part is the added part. The color background part needs RS to participate in the analysis. CERE(II) can be divided into two parts according to different processing methods, separated by thick lines in Table 3. SFNSRM (I) is still used on the left side (processing the relationships between events), and a new method (processing the relationships between RSs) is used on the right side, and they are integrated to form SFNSRM (II).

Transfer relationships among all ce_n and re_m are represented by $tp_{n\to m}$; the transfer relationships among ce_n and rs_l are represented by $tp_{n\to l}$; the transfer relationships among rs_l and re_m, and rs_l and rs_l'(especially RSs in row fields of CERE (II)) have the TPs of 1. The set of TPs is expressed as $TP = \{tp_{n\to m}| n = 1,\ldots,N + L; m = 1,\ldots,M + L\}$. So CERE(II) = ($CE$, RE, RS, TP). It can express the all logical relationships between ce_n and re_m, rs_l and re_m, and among rs_l. The maximum relationship number is $(N + L)\times(M + L)$, and the minimum relationship number is $N + L$.

The number range of TP is $[N + L, (N + L)\times(M + L)]$. $N + L$ means that each ce_n and rs_l causes at least one re_m or $rs_{l'}$ to occur, otherwise ce_n and rs_l are meaningless. $N \times M$ means that all ce_n and rs_l and the re_m and $rs_{l'}$ have logical relationships. When $ce_n \to re_m$ and $ce_n \to rs_{l'}$, then $tp = p_j$; when $rs_l \to re_m$ and $rs_l \to rs_l'$, then $tp = 1$; When there is no logical relationship, $tp = 0$. Therefore, the basic structure of CERE (II) is shown in Eq. (4).

$$\begin{cases} \text{CERE} = (CE, RE, RS, TP) \\ CE = \{ce_n | n = 1, ..., N\} \\ RE = \{re_m | m = 1, ..., M\} \\ RS = \{rs_l | l = 1, ..., L\} \\ TP = \{tp_{n\to m} | n = 1, ..., N + L, m = 1, ..., M + L\} \\ tp_{n\to m} = \begin{cases} 0, \neg(ce_n \to re_m \ or \ rs_l \to re_m) \\ 1, rs_l \to re_m \ or \ rs_l \to rs_l' \\ p_j, ce_n \to re_m \ or \ ce_n \to rs_l \end{cases} \end{cases} \tag{4}$$

Table 3 CERE(II).

	re_1	re_2	...	re_M	rs_1	...	rs_L
ce_1	0	$tp_{1\to 2}$	...	0	$tp_{1\to M+1}$	...	0
ce_2	0	0	...	$tp_{2\to M}$	0	...	$tp_{2\to M+L}$
...	...	...	...	...	0	...	0
ce_N	0	0	...	$tp_{N\to M}$	0	...	0
rs_1	$tp_{N+1\to 1}$	0	0	0	0	...	0
...	...	...	...	...	...	...	...
rs_L	0	$tp_{N+L\to 2}$	0	0	$rs_{L\to 1}$	...	0

The following key definitions are given for SFNSRM (II).

Definition 3. *Matrix of cause event and result event*(*II*) (*CERE* (*II*)), *which is used for the structure representation of SFN, denoted by* $CERE(II) = (CE, RE, RS, TP)$. *Use* ce_n *to denote a specific CE,* $n = 1,\ldots,N$, *its set* $CE = \{ce_n | n = 1,\ldots,N\}$. *Use* re_m *to denote a specific RE,* $m = 1,\ldots,M$, *its set* $RE = \{re_m | m = 1,\ldots,M\}$. *Use* rs_l *to denote a specific RS,* $l = 1,\ldots,L$, *its set* $RS = \{rs_l | l = 1,\ldots,L\}$. *And use* $tp_{n\to m}$ *to denote a specific TP, its set* $TP = \{tp_{n\to m} | n = 1,\ldots,N + L; m = 1,\ldots,M + L\}$.

Definition 4:. *Causal relationship set*(*CRS*): *stores all the events in CERE*(*II*) *and the logical relationships of RSs, denoted by* $\Gamma = \{ce_n \to re_m, ce_n \to rs_l, rs_l \to re_m, rs_l \to rs_l', CE + RS \to rs_l | tp_{n\to m} \times ce_n = re_m, tp_{l\to n} \times ce_n = rs_l$.

CERE (II) left processing mode:

G. CE is equal to RE divided by units in the each row of CERE(II), $CE = RE./\mathrm{CERE}[N,1 \sim M] \to ce_n = [re_{1\sim M}]./\mathrm{CERE}[n,1 \sim M]$. RS is equal to RE divided by units in the each row of CERE(II), $RS = RE./\mathrm{CERE}[N,1 \sim M] \to rs_l = [re_{1\sim M}]./\mathrm{CERE}[N + L,1 \sim M]$.

H. All relationships between $ce_n \to re_m$ and $rs_l \to re_m$ can be expressed as $tp_{n\to m} \times ce_n = re_m$ and $tp_{l\to m} \times ce_n = rs_l$. These relationships constitute CRS, $\Gamma = \{ce_n \to re_m, ce_n \to rs_l, rs_l \to re_m, rs_l \to rs_l' | tp_{n\to m} \times ce_n = re_m, tp_{l\to n} \times ce_n = rs_l, rs_l = rs_l', rs_l = re_m\}$.

I. Starting from a CE-ce_n or rs_l, the RE is found according to the evolution causality, and then the RE is regarded as CE to continue to search for its RE in Γ. The process is cycled until a terminatable RE is found.

CERE (II) right processing mode:

J. The column on the right side of CERE(II) represents the logical relationships between CEs and REs. There are 20 kinds of logical relationships, which constitute set B. $rs_l = \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l))$, $\mathrm{b} \in \mathrm{B}$, $RE + RS$ representing the order of RE and RS, and $\mathrm{CERE}(rs_l)$ representing the *tp* value of rs_l column of CERE(II). Formed CRS: $\Gamma = \{rs_l \to rs_l', CE + RS \to rs_l | rs_l = rs_l', rs_l = \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l))\}$. Then the total CRSs of CERE(II) is $\Gamma = \{ce_n \to re_m, ce_n \to rs_l, rs_l \to re_m, rs_l \to rs_l', CE + RS \to rs_l | tp_{n\to m} \times ce_n = re_m, tp_{l\to n} \times ce_n = rs_l, rs_l = rs_l', rs_l = re_m, rs_l = \mathrm{b}((RE + \mathrm{RS}). \times \mathrm{CERE}(rs_l))\}$.

K. Determine the termination RE-re_m. SFN can be divided into three types: GSFN($\mathrm{a} \to \mathrm{b}$)、MRSFN($\mathrm{a} \to \mathrm{b} \to \mathrm{X}_1$ and $\mathrm{a} \to \mathrm{c} \to \mathrm{X}_1$) and URSFN($\mathrm{d} \to \mathrm{X}_2 \to \mathrm{e} \to \mathrm{X}_3$). When SFN is GSFN or MRSFN, terminating RE is that RE does not result in the occurrence of other CE-ce_n' in CERE (II), then TEPAM, $re_m = \prod(tp_{n\to m} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l)))$, $\exists(ce \to re, ce \to rs, CE + RS \to rs) \in \Gamma$. When a part of SFN has a unidirectional ring structure, $re_m = , \prod(tp_{n\to n'} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l)))$-$(tp_{n'\to m} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l)))^k$ $\exists(ce \to re, ce \to rs, CE + RS \to rs) \in \Gamma$, where: k denotes the number of unidirectional rings. When the TE is not in the ring, it can be calculated according to the above equations. In the ring, only recursive equations similar to the above equations can be obtained, as shown in the last equations in Eqs. (5) and (6).

The SFNSRM(II) of SFN is obtained by the above steps. The CERE(II) model of EE-ce_n leading to TE-re_m is shown in Eq. (5). According to Eq. (5) of the EE-induced TE process, the CERE(II) model of TE for AEIFEP is given as shown in Eq. (6).

$$\begin{cases} CE = RE./\mathrm{CERE}[N, 1 \sim M] \to ce_n = [re_{1\sim M}]./\mathrm{CERE}[n, 1 \sim M] \\ RS = RE./\mathrm{CERE}[N, 1 \sim M] \to rs_l = [re_{1\sim M}]./\mathrm{CERE}[N + l, 1 \sim M] \\ re_m = ce_n \times tp_{n\to m} \\ rs_l = tp_{l\to n} \times ce_n \\ rs_l = \mathrm{b}((RE + RS). \times CERE(rs_l)), \mathrm{b} \in \mathrm{B}, TP = \{tp_{n\to l} | n = 1, \ldots, N + L\} \\ \mathrm{B} = \{\mathrm{b}_{1\sim 20}\} \\ \Gamma = \{ce_n \to re_m, ce_n \to rs_l, rs_l \to re_m, rs_l \to rs_l', CE + RS \to rs_l | \\ \quad tp_{n\to m} \times ce_n = re_m, tp_{l\to n} \times ce_n = rs_l, rs_l = rs_l', rs_l = re_m, rs_l = \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l))\} \\ re_m = \prod(tp_{n\to m} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l))), \\ \quad \exists(ce \to re, ce \to rs, CE + RS \to rs) \in \Gamma, \mathrm{GSFN\ and\ MRSFN} \\ re_m = \prod \dfrac{(tp_{n\to n'} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l)))}{(tp_{n'\to m} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l)))^k}, \\ \qquad \exists(ce \to re, ce \to rs, CE + RS \to rs) \in \Gamma, \mathrm{URSFN}, re_m \text{ in URSFN} \\ re_{mk} = \prod(tp_{n\to n'} ce_{n'} tp_{l\to n} ce_n \times \mathrm{b}((RE + RS). \times \mathrm{CERE}(rs_l)))re_{mk-1}, \\ \qquad \exists(ce \to re, ce \to rs, CE + RS \to rs) \in \Gamma, \mathrm{URSFN}, re_m \text{ not in URSFN} \end{cases} \tag{5}$$

$$\left\{\begin{array}{l} CE = RE./\mathrm{CERE}[N, 1 \sim M] \rightarrow ce_n = [re_{1\sim M}]./\mathrm{CERE}[n, 1 \sim M] \\ RS = RE./\mathrm{CERE}[N, 1 \sim M] \rightarrow rs_l = [re_{1\sim M}]./\mathrm{CERE}[N+l, 1 \sim M] \\ re_m = ce_n \times tp_{n\rightarrow m} \\ rs_l = tp_{l\rightarrow n} \times ce_n \\ rs_l = \mathrm{b}((RE+RS).\times CERE(rs_l)), \mathrm{b} \in \mathrm{B}, TP = \{tp_{n\rightarrow l} | n = 1, ..., N+L\} \\ \mathrm{B} = \{\mathrm{b}_{1\sim 20}\} \\ \Gamma = \{ce_n \rightarrow re_m, ce_n \rightarrow rs_l, rs_l \rightarrow re_m, rs_l \rightarrow rs_l', CE+RS \rightarrow rs_l | \\ \quad tp_{n\rightarrow m} \times ce_n = re_m, tp_{l\rightarrow n} \times ce_n = rs_l, rs_l = rs_l', rs_l = re_m, rs_l = \mathrm{b}((RE+RS).\times \mathrm{CERE}(rs_l))\} \\ re_m = \sum\prod(tp_{n\rightarrow m} ce_{n'} tp_{l\rightarrow n} ce_n \times b((RE+RS).\times \mathrm{CERE}(rs_l))), \\ \quad \exists(ce \rightarrow re, ce \rightarrow rs, CE+RS \rightarrow rs) \in \Gamma, \mathrm{GSFN\ and\ MRSFN} \\ re_m = \sum\prod \dfrac{(tp_{n\rightarrow n'} ce_{n'} tp_{l\rightarrow n} ce_n \times \mathrm{b}((RE+RS).\times CERE(rs_l)))}{(\prod (tp_{n'\rightarrow m} ce_{n'} tp_{l\rightarrow n} ce_n \times \mathrm{b}((RE+RS).\times \mathrm{CERE}(rs_l)))^k}, \\ \quad \exists(ce \rightarrow re, ce \rightarrow rs, CE+RS \rightarrow rs) \in \Gamma, \mathrm{URSFN}, re_m \text{ in URSFN} \\ re_{mk} = \sum\prod(tp_{n\rightarrow n'} ce_{n'} tp_{l\rightarrow n} ce_n \times \mathrm{b}((RE+RS).\times \mathrm{CERE}(rs_l)))(\prod re_{mk-1}), \\ \qquad\qquad \exists(ce \rightarrow re, ce \rightarrow rs, CE+RS \rightarrow rs) \in \Gamma, \mathrm{URSFN}, re_m \text{ not in URSFN} \end{array}\right. \quad (6)$$

Example 2:. *Establish the CERE(II) of the SFEP according to* Fig. 2(c), *as shown in* Table 4.

According to Table 4, we can get: CE = RE {a, d, c, d, e}, RS = {X_1, X_2, X_3}, B = {+,·}, TP = {p_1, p_2, p_3, p_4, p_5, p_6, p_7}. The CRS for the left of CERE(II): Γ = {b = p_1a, c = p_2a, e = X_2, d = X_3}, the CRS for right: Γ = {X_1 = 1-(1- p_4 b)(1- p_5 c), X_2 = p_6dX_1, X_3 = p_3b × p_7e}, therefore, Γ = {b = p_1a, c = p_2a, e = X_2, d = X_3, X_1 = 1-(1- p_4 b)(1- p_5 c), X_2 = p_6dX_1, X_3 = p_3b × p_7e}. Table 4 can be operated according to Eqs.(5) and (6) and related database operations.

In GSFN, the evolution process of TE-b caused by EE-a is: a → b, then TEPAM: b = p_1a.

In the case of unidirectional ring structure, d is in ring of a → b → d and also in unidirectional ring of d → X_2 → e → X_3, then TEPAM:$d = X_3 = 1 - (1-p_3b)(1-p_7e) = 1-(1-p_3p_1a)(1-p_7X_2) = 1-(1-p_3p_1a)(1-p_7p_6dX_1) = 1-(1-p_3p_1a)(1-p_7p_6d\ (1-(1-p_4b)(1-p_5c))) = 1-(1-p_3p_1a)(1-p_7p_6d\ (1-(1-p_3p_1a)(1-p_5p_2a)))$. Finally, when d is cycled k times in d → X_2 → e → X_3, TEPAM: $d_k = 1-(1-p_3p_1a)(1-p_7p_6d\ k-1(1-(1-p_3p_1a)(1-p_5p_2a)))$,$d_0 = p_3p_1a$. Eq. (5) shows that only recursive equations can be obtained when the TE is in the ring.

In Fig. 2(c), events a, b, c are not in the ring, and d and e are in the ring. There is no ring in this case and TE is not in the ring. Therefore, the TEPAM of event d is given only in this case. The AEIFEP is described in the same way as the above process, except that all events in the process are as EEs to cause TEs. All the events except TE in the process are analyzed as EEs in Eq. (5), and then the summation of these TEPAMs is AEIFEP, like Eq. (6). Similarly, the PEO can be used to replace the corresponding event to obtain the TEPCM, which is the probability distribution of the TE. The TEPCM of TE-d, namely the fault probability distribution of d, can be obtained by bringing the fault probability distribution $p_{a\sim e}$ [37] into the Eqs. (5) and (6) under the influence of multiple factors instead of the location of events a, b, c, d and e.

The SFNSRM (II) given in this section is based on SFNSRM (I). It mainly solves the problem that SFNSRM (I) can not express that multiple CEs cause RE through different logical relationships. This problem is also the main reason why it is difficult for general methods to express the SFEP. The logical relationship is described by adding RS to CERE (II) based on CERE (I).

What we need to explain here is that the fault probability distribution is a quantitative expression of SFN for the probability of occurrence of events in SFEP. But for various behaviors in IoT, there are many methods to represent them. For

Table 4 CERE(II).

	a	b	c	d	e	X_{1+}	$X_{2\cdot}$	X_{3+}
a	0	p_1	p_2	0	0	0	0	0
b	0	0	0	0	0	p_4	0	q_3
c	0	0	0	0	0	p_5	0	0
d	0	0	0	0	0	0	p_6	0
e	0	0	0	0	0	0	0	p_7
X_{1+}	0	0	0	0	0	0	1	0
$X_{2\cdot}$	0	0	0	0	1	0	0	0
X_{3+}	0	0	0	1	0	0	0	0

example, it is represented by the probability of completing an action, or the probability of completing the event under the influence of multiple factors (like fault probability distribution). The possibilities of influence among various behaviors in IoT are the TP of connection in SFN, which can be determined according to the actual IoT situation or by using the methods of SFN.

Furthermore, since it is proved that the reliability change of IoTNT can be regarded as SFEP, SFN can be used to describe and study the reliability of IoTNT abstracted from IoT. Then the methods presented in this paper are suitable for IoT reliability research. More generally, the methods are suitable for the representation and reliability study of any SFEP system for any SFEP-compliant systems and systems that can be abstracted as SFEP.

7. Conclusions

In theory, SFN structure representation and research methods are proposed. The methods are suitable for the study of SFEP, and prove that the reliability change of IoT is equivalent to SFEP. Therefore, the methods can be applied to the reliability study of IoT.

(1) It is demonstrated that the process of reliability change of IoT is SFEP and can be studied by SFN. IoT can be abstracted as IoTNT at the system level. The reliability change of IoT is reflected in the reliability change of IoTNT, which is further equivalent to SFEP. SFN is built for SFEP, which is suitable for any system reliability analysis that can be abstracted as SFEP. This paper demonstrates that the behaviors, interactions and processes of IoT are equivalent to the events, connections and network structure of SFN, and proves that SFN can be used for reliability analysis of IoT.
(2) CERE(I) and SFNSRM(I) are proposed. These methods are different from previous SFN research methods. SFN is not converted into SFT, but expressed in matrix form. Based on the established CERE(I), starting from a certain EE, the possible RE and TE caused by the EE are searched. The different TEPAM and TEPCM are obtained considering the different network structures (GSFN, MRSFN, URSFN) and induced modes (EEIFEP, AEIFEP). Based on SFNSRM(I), SFNSRM(II) is proposed and CERE(II) matrix is established. RS is added to CERE(I). The corresponding relationship between the CE and RE and the RS are added to describe the case that multiple CEs lead to REs in different logical relationships. The TEPAM and TEPCM of CERE (II) are given.

In this paper, SFN theory is applied to IoT reliability analysis for the first time. Of course, the characteristics of IOT are also studied in the author's literature [46]. It is also the first time to show the structure representation of SFN internationally. The methods are the independent research methods established for SFN, and get rid of the problem of the original method. It provides a basis for the study of SFNSRM of SFEP, as well as for the intelligent analysis of SFN using computer. But the study is still in its infancy.

Declaration of Competing Interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. All the authors listed have approved the manuscript that is enclosed.

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Appendix.

List of nouns	
Abbreviation	Meaning
IoT	Internet of Things
IoTNT	Internet of Things Network Topology
SFN	Space Fault Network
SFT	Space Fault Tree
CERE	Matrix of cause event and result event, CERE = (CE, RE, TP)
GSFN	General Space Fault Network
MRSFN	Multidirectional Ring Space Fault Network
URSFN	Unidirectional Ring Space Fault Network
TEPAM	TE Evolution Process Analysis Method
TEPCM	TE Evolution Process Calculation Method
SFNSRM	SFN Structure Representation Method
SFEP	System Fault Evolution Process
CE	Cause Event. But, ce is a specific cause event and their set is CE
RE	Result Event. But, re is a specific result event and their set is RE
EE	Edge Event
PE	Process Event
TE	Target Event
PEO	Probability of Event Occurrence
EEIFEP	Edge Event Induction Fault Evolution Process
AEIFEP	All Event Induction Fault Evolution Process
TP	Transfer Probability
CRS	Causal Relationship Set
EC	Equivalence Connection
RS	Relationship Event. But, rs is a specific relationship event and their set is RS
List of variables	
Variables	Meaning
ce_n	A specific cause event, $n = 1,\ldots,N$
N	Number of causal events
re_m	A specific result event, $m = 1,\ldots,M$
M	Number of result events
CE	Generally refers to a cause event; also refers to the set of cause events, $CE=\{\mathrm{ce}_n\| n = 1,\ldots,N\}$
RE	Generally refers to a result event; also refers to the set of result events, $RE=\{re_m\| m = 1,\ldots,M\}$
$tp_{n\rightarrow m}$	Transfer relationship between ce_n and re_m; also represents the value of the transfer probability from ce_n to re_m.

Appendix (*continued*)

TP	Transfer probability set, $TP = \{tp_{n \to m} \| n = 1,\ldots,N;\ m = 1,\ldots,M\}$; refer to transfer probability in general
Γ	Causal relationship set, $\Gamma = \{ce_n \to re_m \| tp_{n \to m} \times ce_n = re_m\}$
Q	Number of influencing factors
p_a	Fault probability distribution of event a under the influence of arbitrary multi-factors
X_{ib}	A relationship event marking logical relationships between events
b	A kind of logical relationship between events
B	A set of all logical relationships, $b \in B$
rs_l	Specially refers to a relationship event in the CERE(II) column field
rs_l'	Specially refers to a relationship event in the CERE(II) row field, $rs_l' = rs_l$
L	Number of relationship events
RS	Relationship event set $RS = \{rs_l \| 1 = 1,\ldots,L\}$; refer to relationship event in general
$tp_{n \to l}$	Transfer relationship between ce_n and rs_l, also represents the value of the transfer probability from ce_n to re_l.
p_j	Transfer probability in SFN, $tp_{n \to l} = p_j$
$p_{a \sim e}$	Fault probability distribution for event a ~ e
CERE $[N,1 \sim M]$	All N rows, $1 \sim M$ columns of CERE
$[re_{1 \sim M}]$	A result event in RE
CERE $[n,1 \sim M]$	nth row, $1 \sim M$ columns of CERE
$ce_{n'}$	Eventually RE, termination event
$\exists(ce \to re) \in \Gamma$	Correspondence relationship existing inΓ
$CE + RS \to rs_l$	Logical relationships of causal events and relationship events causing result events
CERE(rs_l)	The rs_l column in CERE
$P(q_x,q_y)$	RE fault probability distribution caused by CE-x, y occurrence
q_x	The product of fault probability distribution of CE-x and TP, $q_x = p_x \times tp_{x \to m}$ for TEPCM
q_y	The product of fault probability distribution of CE-y and TP, $q_y = p_y \times tp_{y \to m}$ for TEPCM
CE-x	Means event $\times$ is cause event, other similar expressions have the same meaning.
q_b	The product of fault probability distribution of CE-b and TP,
q_e	The product of fault probability distribution of CE-e and TP,
X_1 and X_2	Then two components X_1 and X_2 are selected of the SFT
event b and event e	Two CEs, EEs, in the example

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